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Polymer additives in irrigation water to reduce erosion and better manage water infiltration

ABSTRACT

Water-soluble polyacrylamide (PAM) was identified as an environmentally safe and highly effective erosion preventing and infiltration-enhancing polymer when applied in furrow irrigation water at 1-10 g m^{-3}, i.e. 1-10 ppm. The agricultural use of polyacrylamide, PAM, as an additive in irrigation water has grown rapidly since commercial introduction in 1995 because it improves water infiltration and reduces erosion-induced soil losses up to 97%, saving tons of topsoil per hectare per year. Various polymers and biopolymers have long been recognized as viable soil conditioners because they stabilize soil surface structure and pore continuity. The new strategy of adding the conditioner, high molecular weight anionic PAM, to the irrigation water in the first several hours of irrigation enables a significant costs savings over traditional application methods of tilling soil conditoner into the entire (15 cm deep) soil surface layer. By adding PAM to the irrigation water, soil structure is improved in the all-important 1-5 mm thick layer at the soil/water interface of the 25 to 30% of field surface contacted by flowing water. Recent studies with biopolymers such as chitosan, charged polysaccharides, whey, and industrial cellulose derivatives show potential as biopolymer alternatives to PAM. Their success will depend on production economics.

INTRODUCTION

Increasingly, agricultural production is being forced by urban development and resource competition to marginal land where modern irrigation technologies are essential for economic production levels. With irrigation, however, comes the age-old problem of erosion, a constant threat to agricultural productivity and to our environment. Soil run-off from furrow-irrigated fields removes 6.4 tons of topsoil per acre per year on average (1-3). The eroded soil carries residual agricultural chemicals into downstream waterways and other riparian surface waters.

Arid soils generally erode easily because they tend to be low in organic acids and natural polysaccharides that provide structure and protect the soil against the shearing forces of running water. Once soil particles are detached from the furrow, they are easily carried from the field in runoff. One highly effective method for reducing erosion is to enhance soil structure by adding conditioners, i.e. synthetic and naturally derived polymers that improve soil cohesion (4-7). In various studies of conditioners, polyacrylamide-based polymers or "PAM" polymers were identified as an effective class of soil stabilizer (6-7). In its original mode of application, PAM was sprayed and tilled onto fields using as much as 100-300 kg/hectare in order to modify soil structure in the entire tilled surface layer. Such applications ultimately proved unwieldy to most farmers due to the numbers of field passes during application and the high cumulative cost of the polymer additive. PAM use as a soil conditioner was generally reserved for greenhouse work, high value horticultural or nursery crops, and research efforts - projects which can tolerate high materials costs.

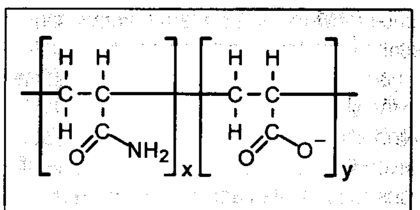
Recently, Lentz *et al.* (1,3) introduced an ideological breakthrough in the use of PAM soil conditioners - adding small quantities of PAM to the in-flowing water during furrow irrigation (1,3,8-14). By the addition of 5-20 ppm of high molecular weight PAM to irrigation water in the first several hours of irrigation, soil losses of a highly erodible soil were reduced by up to 97%. At these concentrations, polymer use for a hectare is approximately 0.5-1.0 kg per irrigation, with seasonal application totals ranging from 2 to 6 kg per hectare. This implies a substantial saving compared to the cost of treating the "entire" tilled surface layer (15 cm depth) with 100 or more kg of PAM per hectare. By adding PAM to the irrigation water, the water itself is the means of delivery; i.e. no extra application methods are required. Furthermore, only the soil in contact with the irrigation water is treated, resulting in improved soil structure in the 1-5 mm thick layer at the soil/water interface of furrow irrigated soils. These few millimeters, however, are the most critical for controlling erosion.

Since PAM-use is such an effective and economical technology for reducing soil-runoff, it has found significant application in the U.S., Australia, Canada, Portugal and Latin America. PAM-use has spread beyond agricultural use to stabilization of construction sites and road cuts, with formal statewide application standards set in Wisconsin, and Washington state and soon expected in several Southern U.S. states.

With such widespread success, application of polymers to irrigation water and related uses merit expanded consideration for soil conservation and water quality protection in the US and around the world. This paper describes the application of soil stabilizing polymers as irrigation water additives by i) detailing some of the functional attributes of PAM that make it effective in reducing erosion-induced losses and improving infiltration; ii) briefly outlining key environmental considerations of PAM-use and iii) discussing potential alternatives to PAM for agricultural applications. Since PAM is a synthetic polymer that was not designed to achieve both biodegradability and functional performance, this final section focuses on biodegradable biopolymers. Recent studies with biopolymers such as charged polysaccharides (15-17), whey (18), and industrial cellulose derivatives (15,17) show that some "degradable" polymers impart many of the primary functional attributes of PAM with the added advantage of more rapid compostability.

POLYACRYLAMIDE, PAM

The term polyacrylamide and acronym "PAM" is a general lexicon for a broad class of acrylamide-based polymers varying in chain length, charge type, charge concentration, and the number and types of side-group substitutions (19-22). PAM sold commercially for erosion control is typically a charged copolymer with roughly 20-30% of the acrylamide chain segments replaced by an acrylic acid group (Scheme 1).



Scheme 1- PAM: Poly(acrylamide-co-acrylic acid)

As such, this polymer generally exhibits a negative charge in water. Molecular weights of PAM used for irrigated agriculture range from 3 to 15 million g/mole, with the more common commercial products in the range of 12-15 million g/mole - corresponding to over 150,000 monomer units per chain. Because of its size and structure, PAM attracts soil particles via coulombic and Van der Waals forces (15,19,20-23), as outlined in a simple schematic shown in Figure 1. Ionic bridges, i.e. the attraction of opposite charges between polymer and soil particles, create large stable aggregates of PAM and soil. Interestingly, anionic PAM has been shown to be effective on anionic soil. How do entities of the same charge interact? It is believed that counter ions in either the water or soil, such as calcium and magnesium, interact with the polymer and soil particles to form these ionic bridges (19,20,22,23). Besides ionic bridges, soil aggregates are further stabilized by chain bridging, whereby a single polymer chain spans between separate soil particles (Figure 1). The high molecular weight of the polymer allows a chain to interact with multiple particles, creating a network of stabilized particles.

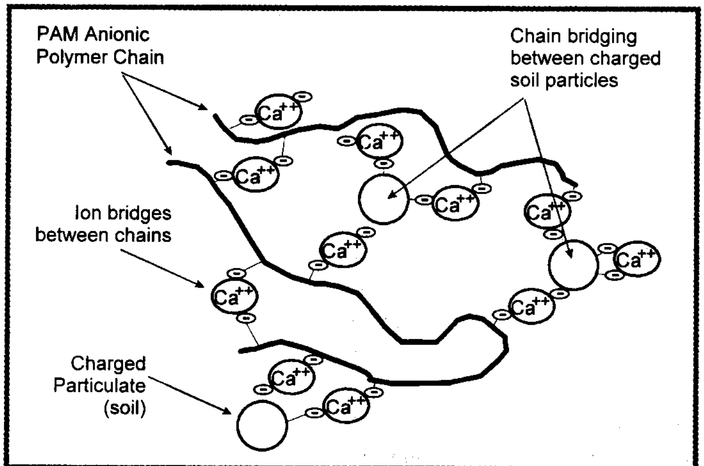


Figure 1 - Schematic depiction of the interactions of anionic PAM with charged soil particles in the presence of calcium

The effect of the molecular weight of PAM on reducing soil run-off is outlined in Figure 2. Results are shown for both field studies by Lentz and Sojka (8,20) and lab-scale, mini-furrow studies by Orts et al. (15). Trends for both studies are generally similar. If the molecular weight, MW, is below 200-thousand, PAM is not very effective in either field or lab-scale furrows. In other words, the concentration of solids in the run-off is similar to that from a control furrow, i.e. from a furrow with no polymer added to the irrigation water. In the MW range between 200,000 and ~6 million, the effectiveness of PAM treatment increases significantly with MW, reaching a concentration of solids in the run-off of less than 10% of the control furrow at MW of 6 million. For MW above 6 million, the solids content in the run-off water shows little relative improvement with increasing MW. These trends highlight the requirement that the commercial PAM used for agricultural erosion control have a MW in the millions. Because of their large chain size, PAM copolymers used agriculturally have not always solubilized readily into water. In the early stages of commercial PAM-use, farmers complained that PAM application sometimes required vigorous agitation at the PAM input port. PAM suppliers have generally overcome this issue by providing PAM that readily dissolves in water, and introducing pre-mixed PAM solutions and emulsions for rapid, steady application.

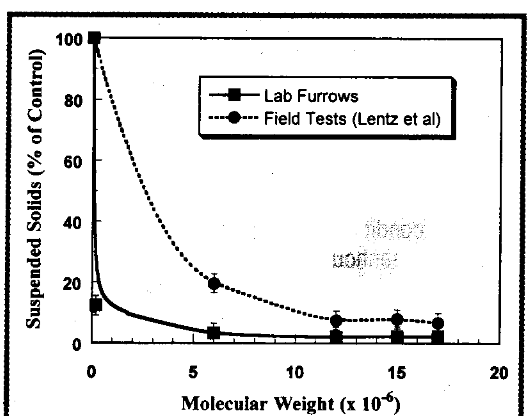


Figure 2 - Results of lab-scale furrows and field furrow tests showing the effect of molecular weight on the effectiveness of PAM in preventing water-induced runoff

PAM APPLICATION STRATEGIES FOR EROSION CONTROL

Lentz and Sojka (1,3) reported a 94%.

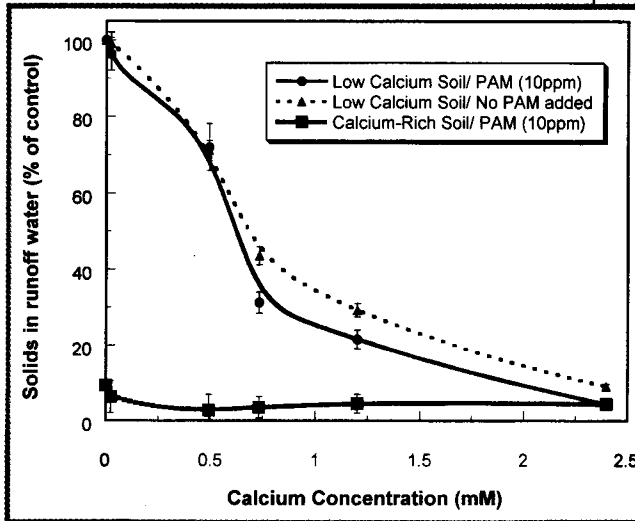


Figure 3 - The effect of added calcium on suspended solids in soil run-off from lab-scale mini furrows using soil both low and high in calcium. In the low calcium soil, PAM had little effect on reducing solids content due to erosion effects

reduction in runoff sediment loss over three years, using the national NRCS application standards, a set of U.S. guideline established in 1995 for agricultural PAM (14). The 1995 NRCS standard calls for dissolving 10 ppm (or 10 g m-3) PAM in furrow inflow water as it first crosses a field - typically the first 10 to 25% of an irrigation duration - then halting PAM dosing when runoff begins at the end of the field. Under many circumstances, applying PAM continuously at 1-2 ppm for the full irrigation cycle can be equally effective, although continuous application at 0.25 ppm PAM was shown to be a third less effective than at 1 ppm (24).

PAM has been used increasingly throughout the world on an increasing variety of soils. As implied by the schematic in Figure 1, counter-ions, such as calcium, play a considerable role in PAM/soil aggregate formation. As such, the ionic composition of the water also plays a considerable role in the effectiveness of PAM. Despite this increasing application of PAM to an array of soil types, with differing water chemistries, the NRCS standards (14) have generally been appropriate.

PAM AND INFILTRATION

The water infiltration rate is usually higher for PAM-treated furrows than for untreated furrows (1,3,24-29), although this effect depends on soil texture. For silt loam soils, infiltration is typically 15% higher than untreated furrows while for various clays this effect results in up to 50% infiltration increase (24). Bjorneberg et al. (26) discussed the mechanisms for this increase and suggested that improved infiltration is related to viscosity effects. In tube diameters >10 mm, PAM viscosity does not rise sharply until PAM concentration is >400 ppm. However, in small soil pores, the "apparent viscosity" increases significantly, even at the low PAM concentrations (10 ppm) used for erosion control (27). Most likely, PAM infiltration effects are a balance between prevention of surface sealing and apparent viscosity increases in soil pores (26-29). In medium to fine textured soils, maintenance of pore continuity via aggregate stabilization is more important. In coarse textured soils, where PAM achieves little pore continuity enhancement, infiltration effects are nil or even slightly negative, particularly above 20 ppm (24). Because PAM prevents erosion of furrow bottoms and sealing of the wetted perimeter, water moves across silt loam soils about 25% further laterally compared to non-treated furrows (8). This can be a significant water conserving effect for early irrigations. Farmers should take advantage of PAM's erosion prevention to improve field infiltration uniformity by increasing inflow rates two to three fold (compared to normal). Increased flowrates result in more uniform infiltration between the inflow and outflow ends of furrows (24).

SPRINKLER APPLICATION OF PAM

Farmers and agronomists are showing increasing interest in using PAM during sprinkler irrigation to prevent run-off/run-on problems, and to establish irrigation uniformity (11,12,25,26,30,31). PAM sprinkler application rates of 2 to 4 kg ha-1 were shown to reduce run-off 70% and soil loss 75% compared to controls (30). Multiple groups (12,25,26,28) report improved aggregate stability from sprinkler-applied PAM, leading to decreased runoff and erosion. Flanagan et al. (11,12) increased water infiltration into the soil using 10 ppm PAM, which they attributed to reduced surface sealing. However, the effectiveness of sprinkler-applied PAM is more variable than for furrow irrigation because of application strategies and system variables that affect water drop energy, the rate of water and PAM delivery, and possible application timing scenarios. In general, a sprinkler application of PAM usually requires higher seasonal field application totals for efficacy compared to furrow irrigation (31). Commercially, farmers with sprinkler infiltration uniformity problems (i.e. run-off or run-on) because of the use of wide sweeping center pivot sprays on steep or variable slopes, have begun to see the most significant effects of PAM compared to other sprinkler conditions.

WATER EFFECTS: CALCIUM AND THE EFFECT OF IONS

Several groups have reported that improvements in soil run-off are not strictly a factor of the soil type or polymer additive, but also dependent on the ionic composition of the water (22,23). In fact, erosion control can be achieved without the addition of PAM by adding exchangeable calcium, such as gypsum (23), or other ions that improve electrical conductivity. Orts et al. (22) explored this result further by utilizing a highly calcareous soil with a pH of 8.4 and a low concentration of soluble, exchangeable calcium. In particular, this soil was chosen because it did not interact well with PAM, especially using the relatively clean, ion-free water found in Northern California, U.S.A. As shown in Figure 3, calcium alone significantly reduced suspended solids in the runoff from this soil. PAM and calcium together had a greater effect in reducing suspended solids than calcium alone. The results in Figure 3 are clearly not universal, merely presented here to highlight the interplay between soil type, water composition, and PAM properties. Many sources of irrigation water have a much higher electrical conductance or exchangeable calcium than the tap water used in that study. More notably, the benefit from added calcium is short term. Calcium must be added continuously to the irrigation water. In contrast, PAM can be added for a short period during an initial irrigation series, and provide a lasting effect for weeks without additional doses.

ENVIRONMENTAL IMPACT OF PAM

The overriding environmental impact of PAM is reduced erosion-induced sediment loss in runoff (1,3,8), with corresponding reductions of entrained chemical residue reaching riparian waterways. For example, PAM prevents yearly topsoil run-off of up to 6.4 tons per acre (1) and at least three times that as on-field erosion (24,32). Since toxic pesticides and herbicides are transported via soil sediment to open water and then eventually into the air, there is an increasing need to prevent soil run-off. Recently PAM was shown to sequester biological and chemical contaminants of runoff, providing significant potential for reduced spread of phytopathogens, animal coliforms and other organisms of public health concern (32).

The main environmental concerns in PAM-use revolve around polymer purity (19), and issues related to biodegradation/accumulation (33-39); i.e. since PAM degrades slowly, the long-term, unknown effects on organisms must be considered. Biological degradation of PAM incorporated into soil is about 10% per year (35,37). However, low application rates and shallow surface application is thought to accelerate degradation via various pathways, including deamination, shear-induced chain scission and UV photosensitive chain scission (35-37). Even at 10% annual degradation, PAM accumulation is insignificant at these application rates. Lentz and Sojka (39) showed that only 1 to 3% of applied PAM leaves fields in runoff and that this is quickly adsorbed by entrained sediment or ditch surfaces. Barvenik (37) noted that anionic PAM is safe for aquatic organisms at surprisingly high concentrations, with LC50>50 times the inflow dosage rates. Water impurities further buffer environmental effects by quickly deactivating dissolved PAM (38). Considering that the acrylamide monomer used to synthesize PAM is a neurotoxin, care must be taken by PAM supplies to ensure polymer purity. The EPA recently reviewed the use of PAM with USDA and polyacrylamide industry scientists, and concluded that the acrylamide monomer concentrations of <0.05% found in products for use during furrow irrigation are acceptable, with minimal amounts of monomer released into the environment (39). The first step in the biodegradation of PAM is early removal of the amine group from the polymer backbone(40-41), with reversion to acrylamide monomer thermodynamically unfavorable (33,37). Although these environmental issues about PAM are raised, PAM is widely recognized as a safe, environmentally friendly, hygienically safe and cost-effective flocculating agent. It has been used industrially for decades as a soil conditioner, in food processing, as an additive in animal feeds and in various water treatment processes.

BIOPOLYMER ALTERNATIVES TO PAM

PAM's successful use in irrigation water to reduce erosion and improve infiltration has raised questions of whether other polymers can be used in this application. There is increasing anecdotal and scientific evidence that anionic PAM efficacy varies with different soils and waters. Variations include sodicity, texture, bulk density, and surface charge-related properties. It would be beneficial to have a wide array of polymers with potentially different soil-stabilizing mechanisms, applicable to different soil types.

Of course, any reduction in price would also benefit farmers. The market price of PAM, i.e. several U.S. dollars per kilogram, is high relative to many commodity polymers, such as polyethylene, polypropylene, and polystyrene. Treatment for one year can cost up to $ 25 (U.S.) per hectare, which is still cost competitive with conventional erosion abating technologies such as straw bales, settling ponds, and underground or drip irrigation systems. The increasing market pull of organic farming techniques is a strong reason to explore alternatives to PAM. PAM cannot be used during organic farmering because it is a synthetic polymer derived from non-renewable resources. Natural polymers, which often degrade via relatively benign routes, may be more suitable. Biopolymer alternatives to PAM would likely have marketing advantages due to public perception of being safer. Cellulose and starch xanthates were among the first industrial biopolymers shown to stabilize soil (15,17). Menefee and Hautala (17) reduced sediment runoff by nearly 98% by surface treating 20° sloped plots with cellulose xanthate solution (0.4%). Orts et al (15) added cellulose xanthate to the irrigation water of lab-scale mini-furrows, and reduced erosion 80% when xanthate was applied at concentrations of 80 ppm or greater, which is well above the standard PAM application rate of 10 ppm.

Chitosan, the biopolymer derived from crab and shrimp shells, was shown to reduce erosion losses as effectively as PAM in lab-scale mini-furrow at concentrations of 20 ppm (22). With such favorable lab test results, chitosan was further tested in a field test at the USDA Northwest Irrigation and Soil Research Lab, Kimberly ID. In the field, chitosan reduced erosion-induced soil losses by, at best, half of the control, but far less effectively than PAM. Such poor comparative results, however, do not mean that chitosan had no effect on the irrigation. Observations of the furrows treated with chitosan revealed remarkable results in the first ~20 meters of the furrow. In fact, chitosan acted as such an effective flocculating agent that it removed fine sediments, and even algae from the irrigation water. Perhaps chitosan binds so readily with sediment that it flocculates out of solution near the top of the furrow. The major drawback of chitosan is its market cost of >$ 7/kg, roughly twice the price of PAM.

SUMMARY

U.S. agricultural PAM-use for erosion control and infiltration improvement reached 400,000 ha in 1999, with U.S. and worldwide markets expected to grow as farmers recognize PAM's efficacy, and as government-mandated water quality legislation is realized. The success of PAM in agriculture opens the possibility to explore other Ag-related uses for PAM, as well as the potential to find alternatives to PAM. For example, modified polysaccharides and cheese whey, the protein concentrate from cheese processing, are particularly interesting natural soil stabilizers, and could be used to treat irrigation water.

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